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Damage Mitigation Strategies of 'Non-Structural' Infill Walls: Concept and Numerical-Experimental Validation Program

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ABSTRACT: In the past design codes, infill panels/walls within frame buildings have been considered as non-structural elements and thus have been typically neglected in the design process. However, the observations made after major earthquakes even in recent times (e.g. Duzce 1999, L'Aquila 2009, Darfield 2010) have shown that although infill walls are considered as non-structural elements, they can interact with the structural system during seismic actions and modify the behaviour of the structure significantly. More recent code design provisions (i.e.,NZS4230, Eurocode 8, Fema 273) do now recognize the complexity of such interactions and require either a) consider these effects of frame-infill interaction during the design and modelling phase or b) assure no or low-interaction of the two systems with proper detailing and arrangements in the construction phase. However, considering the interaction in the design stage may not be a practical approach due to the complexity itself and in most cases does not solve the actual problem of brittle behaviour and thus damage to the infills. Therefore, the purpose of this particular research is to develop technological solutions and design guidelines for the control or prevention of damage to infill walls for either newly designed or existing buildings. For that purpose, an extensive experimental and numerical research programme has been planned. The concept, background on infill practice in New Zealand and the research programme will be briefly described in this paper.

1 INTRODUCTION

Modern seismic codes prioritize the life safety criteria in the seismic design of structural systems, which allows plastic hinging in certain structural members without causing a loss of global stability. In recent seismic events (e.g., L'Aquila 2009 earthquake as shown in the Figure 1a), many of the structures didn't collapse, but suffered unexpectedly extensive damage at columns, beams, beam-column joints, and infill walls due to the interaction with infills. However, the failure of 'non-structural' infill walls may very well be a significant threat for human life both inside and outside of the building as they are usually the first elements to experience damage even under moderate seismic events, which are usually considered less important during the design process. However, due to their brittle behaviour, the infill walls can modify the behaviour of the structure as a whole, drastically altering the expected behaviour by the designer and enabling undesirable failure modes. For that reason, two design alternatives have been suggested by Paulay and Priestley 1992. These design alternatives have been included in NZS 4230:2004:

a) *When infill panels are constructed without full separation from the frame, the composite action must be considered in analysis and designed accordingly.*

b) *It should be noted that even where sufficient separation is provided at top and ends of a panel, the panel will still tend to stiffen the supporting beam considerably, concentrating frame potential plastic hinge regions in short hinge lengths at each end, or forcing migration of hinges into columns, with a breakdown of the weak-beam, strong-column concept.*

Although those two alternatives have been given in the NZS4230, there are no specific guidelines which support the design process of the cases mentioned above. Considering a), it has not been shown how to take the infills into account, leaving the engineers with many options. This subject has been studied by many researchers. Usually, diagonal compression strut(s) models have been developed and used to structurally represent the masonry infill walls (i.e. Crisafulli 1997, Figure 1b-c). However, for practitioner engineers, due to the variety of the infill types, it is still difficult to predict/model the complex nature of interaction between structural systems and infill walls. Furthermore, extensive modelling often does not solve the structural problems related to the brittle nature of infill walls.

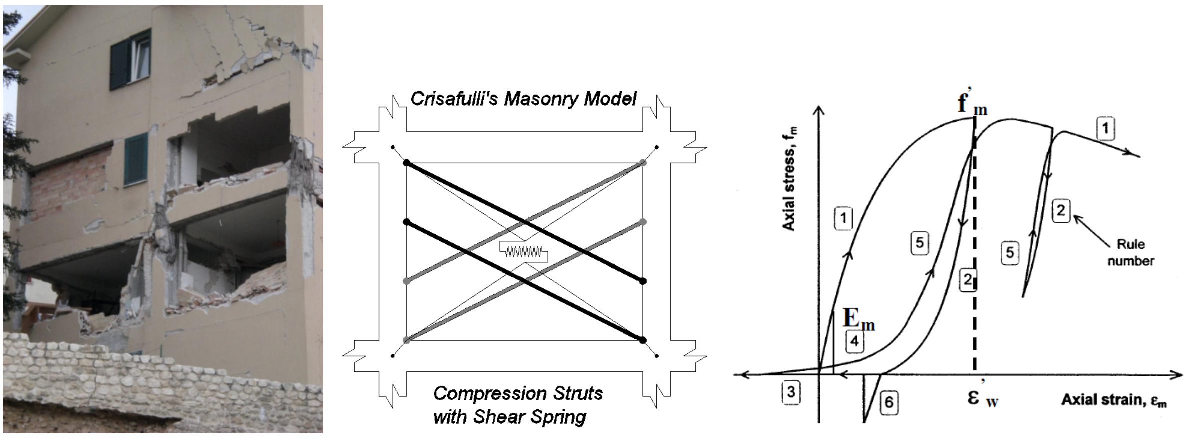

Figure 1 a) L'Aquila 2009(Courtesy of S. Pampanin), b) Masonry Infill Model with Equivalent Diagonal Compression Struts, c) Strut Hysteresis Rule (Crisafulli 1997, Carr 2010)

On the other hand, for case b), while a sufficient separation can eliminate the complexity of modelling the infills and mitigates the effects from the infill-frame interactions, but it might activate out-of-plane failure mechanism of the infill walls. For the required separation, in NZS 4230:2004, a reference has been given to NZS 1170.5:2004. However, a method to provide the sufficient separation without causing the identified structural problem in b) has been left unanswered. Therefore, it seems that there is still a missing state-of-the-art in providing proper details and reliable models for the isolation of infill walls.

In the light of the information given above, the purpose of the reported research may be summarized as a development of technological solutions and design methods for preventing/minimizing in-plane and out-of-plane failures of infill walls for new buildings. However, the outcomes of this research may also be adapted as a retrofit solution for existing buildings. In this paper, the concept, background on infill practice and the research programme will be reported. Since the research is still at a preliminary stage and no testing has yet been performed, this paper shall be considered a progress report.

2 CONCEPT

It is widely known and reported that infill walls in reinforced concrete frame buildings cause an 'increase' in lateral stiffness, strength, and energy dissipation capacity (Mander et al. 1993, Mosalam et al. 1997, Crisafulli 1997, Lee and Woo 2002, Magenes and Pampanin 2004, Dolsek and Fajfar 2008). Whether this behaviour is favourable or not, the infill walls are usually the first elements to be damaged in seismic events. There are four typical modes of damage in infill walls; crushing at the center of the panel, crushing at the corners, sliding shear failure, and diagonal tension cracks. These failure patterns are shown in Figure 2.

Recent researches have shown that the cost related to the failure of a non-structural component in a building may easily exceed the replacement cost of a building (Villaverde 1997), which is due to the loss of inventory, loss of business, downtime, etc. Therefore, there exists a current need to develop affordable technological solutions to prevent damage to infill walls.

In order to explain the conceptual idea of this research, an example base shear lateral drift graph is provided in Figure 3. The conceptual idea is to apply innovative solutions such that the brittle behaviour of the infill walls will be modified into a more favourable one for seismic actions. Therefore, the damage to infill walls at moderate seismic events will be prevented/minimized and the energy dissipation will occur by other sources instead of damaging the infill walls.

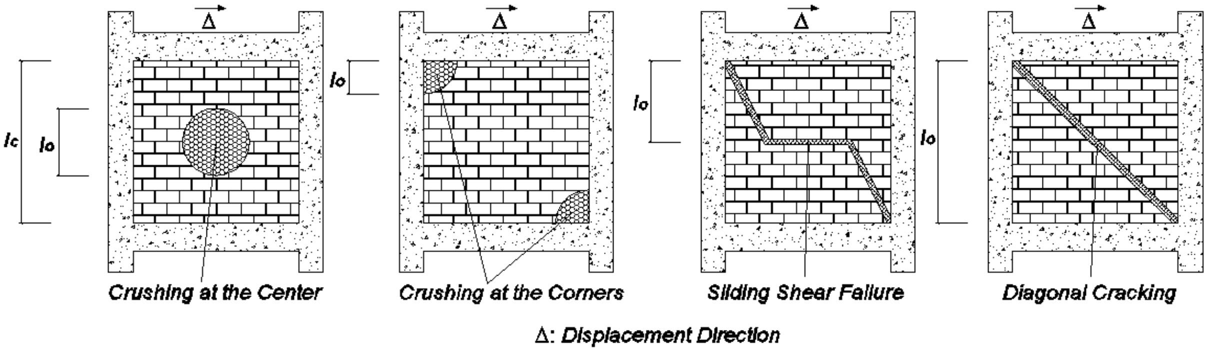

Figure 2 Typical Failure Patterns of Infill Walls/Panels

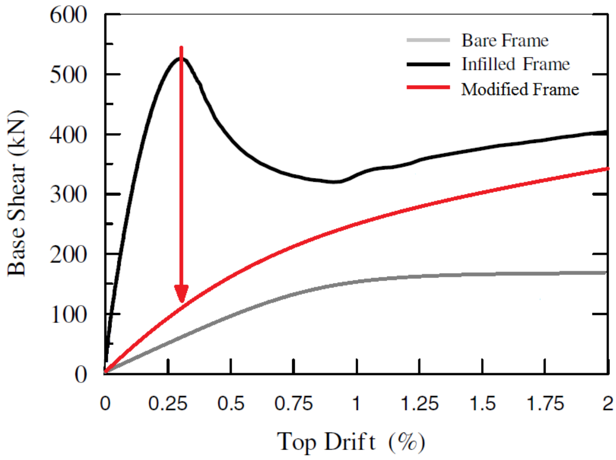

Figure 3 A Sample Base Shear vs. Lateral Drift Curve for Infilled and Bare Frames (Original Graph is Taken from Magenes and Pampanin 2004)

There have been many researches that focused on strengthening of R/C infilled frames (e.g. Akin 2009, Akguzel 2003). However, most of these studies have been carried out in order to increase the lateral load capacity of pre-70s buildings and the aim has not been the prevention of damage to infill walls, but rather has been the prevention of collapse of the whole structure, which is reasonable considering the weaknesses of pre-70s buildings. On the other hand, very few researches focused on the prevention of damage to infill walls (Calvi and Bolognini 2001).

Therefore, considering the effects of infill walls in the structural behaviour, several state-of-the-art technological solutions and design methods will be investigated in order to both 1) prevent damage to infill walls, and 2) eliminate the unfavourable effects of infill walls on the structural response while utilizing their favourable contribution near the collapse limit state (i.e. infill walls may act as a fuse to protect the global stability in the case of collapse).

3 BACKGROUND ON INFILL PRACTICE IN NEW ZEALAND

A structural inventory survey/preliminary assessment for critical pre-70 R/C buildings in Christchurch City Business District (CBD) has been carried out as part of an FRST-funded research project (FRST Retrofit, 2010). As part of the survey, the different types and configurations of infill types for these older vintage R/C buildings are sampled. Figure 4a shows the distribution of different infill types, and Figure 4b shows the common critical structural deficiencies in these buildings. Short column effect, a result of the presence of half-height infill walls or spandrel beams, is the most common type of critical weakness.

In addition, the building code requirements in relation to the infill practice in New Zealand, starting from the NZS 95(1935) up to the present NZS 4230 (2004) have been reviewed and summarised herein.

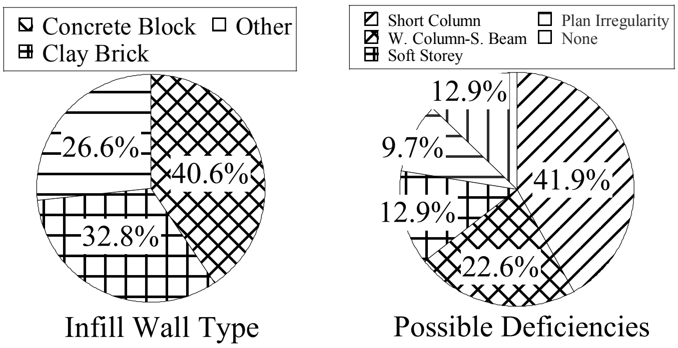

Figure 4 a) Infill Wall Types and b) Possible Deficiencies of Pre 1970 R/C Buildings in Christchurch CBD

According to the standard NZS 95 Part V and VI (1935), panel walls should be constructed of stonework, brickwork, concrete or a combination of them and panel walls shall be properly secured to the concrete frame. Also it is stated that those panel walls can be constructed of single skin wall or cavity wall (double skins with a cavity in between). Usually, the interior walls had been constructed as single skin and the exterior walls had been constructed as cavity walls for water proofing purposes. Surprisingly, NZS 95 also states that it is possible to construct the infill walls as reinforced brickwork, for increased preventive measure and lateral resistance against earthquake. Note that the definition given before the mention of reinforced brickwork is referring to unreinforced masonry panel walls.

No separate standard specification for concrete bricks and concrete blocks existed until NZSS 595 (1952) and it introduced the following definitions:

- ‘Concrete brick’ means a solid or hollow concrete masonry unit of nominal dimensions of 9 in. in length (228.6 mm), 4.25 in. in width (107.95 mm), and 3 in. in depth (76.2 mm)
- ‘Concrete block’ means a solid or hollow concrete masonry unit, any one of the nominal dimensions of which differs from the corresponding dimensions of a concrete brick

In 1964, many important definitions for practices in wall construction were made in NZSS 1900:1964:

- ‘Infilling Panels’ means any wall between beams, columns, or floors which by virtue of its position and construction is subject to induced and/or applied loadings (e.g. Figure 5a)
- ‘Partition Wall’ means a wall which by virtue of its position and construction does not contribute to the strength or rigidity of a structure (e.g. Figure 5b)
- ‘Reinforced Grouted Brick Masonry’ means a construction of two or more skins of brick between which reinforcing steel is embedded in grout (e.g. Figure 5c)
- ‘Reinforced Hollow Masonry’ means masonry of cellular units having reinforcement in filled cells (e.g. Figure 5d)
- ‘Reinforced Masonry’ means any masonry in which reinforcing steel is so bedded and bonded that the two materials act together in resisting forces
- ‘Shear Wall’ means a structural wall which because of its position and shape, makes a major contribution to the rigidity and strength of a building

When structures up until the 1960s are examined, it has been observed that although the first concrete block and concrete brick standard was published in 1952, many buildings continued to be built by clay bricks. The use of unreinforced clay bricks was also permitted. After the introduction of NZSS 1900:1964, use of concrete block masonry flourished, and the number of projects that used concrete block masonry as infill increased. A new type of seismic resisting system, which relied on reinforced concrete block masonry for lateral stiffness and strength, without R/C framing, was also introduced and widely used in the 1960s (Holmes, 1965)

In NZS 4230:2004, the word ‘masonry’ has been used for many kinds of infill wall or wall construction materials. Moreover, ‘Masonry Unit’ has been defined as ‘a preformed component intended for use in reinforced concrete masonry construction with cells laid in the vertical direction and with face-shell-bedded joints’. NZS 4230:2004 superceded NZS 4230P:1985, although it remained very similar. Therefore, it can be deduced that the first standard to give guidelines for the design of infill walls in reinforced concrete frames was NZS 4230P:1985 and with only limited changes in the 2004 edition, largely remains the current state-of-the-art.

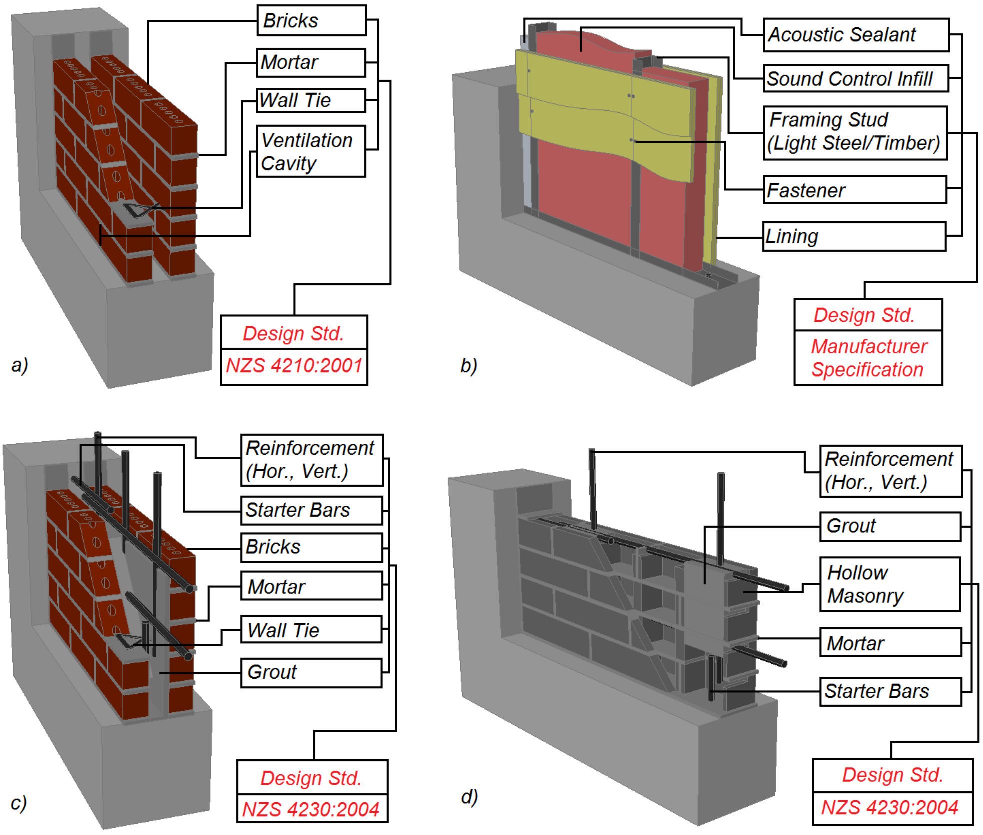

Figure 5 a) Unreinforced Masonry Infill, b) Light Steel/Timber Framed Wall, c) Reinforced Grouted Brick Masonry, d) Reinforced Hollow Masonry

Table 1 Some Standardized Dimensions for the Units in Figure 5

Infill Type	**t_m(mm)**	**d_{wth}, d_{wtv} (mm)**	**d_{vc}, h_{vc} (mm)**				
a) Unreinforced Masonry	≤10	≤600, 400	≤800, 75				*t_m: Mortar Thickness* *d_{wth}: Wall Tie Spacing in Horizontal* *d_{wtv}: Wall Tie Spacing in Vertical* *d_{vc}: Ventilation Cavity Spacing* *h_{vc}: Ventilation Cavity Height*
	d_{fs}(mm	**t_e (mm)**	**h_w (mm)**	**t_{sci} (mm)**	**t_l (mm)**	**d_f(mm)**	
b) Light Steel/Timber Framed Wall	≤600	15	≤3600	75	10, 13	300	*d_{fs}: Framing Stud Spacing* *t_e: Expansion Gap at the Top of the Frame* *h_w: Wall Height* *t_{sci}: Sound Control Infill Thickness* *t_l: Thickness of Linings* *d_f: Fastener Spacing*
	t_m(mm)	**d_{wth}, d_{wtv} (mm)**	**t_w(mm)**	**ρ_R (%)**			
c) Reinforced Grouted Brick Masonry	≤10	≤600, 400	≥140	≥0.07			*t_w: Wall Thickness* *ρ_R: Reinforcement Ratio over the Gross Wall Area in the Perpendicular Direction to the Reinforcement*
d) Reinforced Hollow Masonry	≤10		≥140	≥0.07			**For More Information Refer to the Related Standards Shown in the Figures**

Currently in New Zealand, mostly light steel/timber framed partition walls (or Drywalls, a sample shown in Figure 5b) are being used as infill walls in combination with many available cladding options for the exterior. The first examples of drywalls were manufactured and used in 1927 and since then they have been increasingly used in New Zealand. The specifications for these infill types are given by the manufacturers and the main parameters are dependent on acoustic and thermal insulation capabilities of the walls. Light steel framed dry walls are specified as non-load bearing due to their friction fitted sliding connection details. However, timber framed dry walls are specified as load bearing due to their full connection to the surrounding frame (GIB®2006).

Nevertheless, in many overseas countries such as southern Europe, Mid-East Asia, and South America, the use of unreinforced masonry bricks/blocks in infill walls still constitutes a major portion of infilling practice.

4 RESEARCH PROGRAMME

4.1 *Test Setup and Testing Procedure*

A full scale, 2D single-storey single-bay reinforced concrete frame has been planned and designed for experimental study. It will consist of beams and columns connected by two 40mm diameter post tensioning bars, post tensioning force of which can be adjusted according to the targeted drifts. The post tensioned R/C frame is expected to have no or negligible damage after each test and designed considering various possible failure patterns of the infill walls. Due to the rocking of the connections, the global behaviour of the frame will not change. Therefore, during the experiments, only the behaviour of the infill walls and the various infill-to-frame connections will govern the response; thus the same frame will be used multiple times by only changing the infill walls.

Experiments will be carried out using displacement controlled reverse cyclic quasi-static loading. The testing protocol to be used in each test has been prepared according to ACI 374.1-05. The test setup, measurement system, reinforcement detailing, and the testing protocol are given in Figure 6. It should be noted that although the testing protocol shows a maximum drift of 5%, the as-built infill wall tests will likely be finalized around 3% drift ratio since similar studies reported a maximum drift ratio between 1% and 2% for the failure of infill walls.

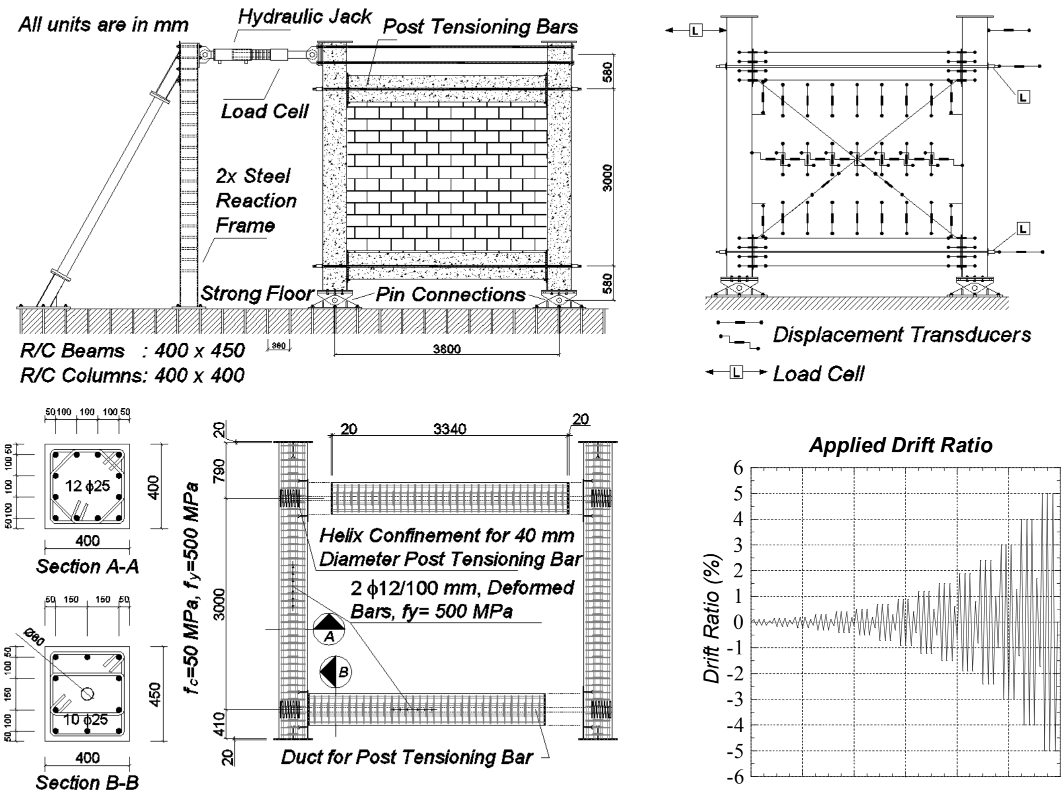

Figure 6 Test Setup, Measurement System, Reinforcement Detail, Testing Protocol

4.2 *Test Specimens*

Considering the information outlined in Section 3, three types of materials are going to be used for the infill walls, which are clay bricks, concrete blocks, and light steel framed walls (or partition/drywalls) so that both New Zealand and overseas practice in infill walls will be covered. The specimen types have been summarized below in Table 2.

Table 2 Test Specimens

Specimen Type	Specimen Name	Post Tensioning Force per Bar (kN)	Infill Type	Number of Tests	Concrete Compressive Strength (Mpa)	Steel Tensile Strength (Mpa)	Boundary Conditions Around the Walls
Type I Bare Frame	BF200	200	None	2	50	500	None
	BF300	300		2	50	500	
	BF400	400		2	50	500	
Type II Fully Infilled Frame	FI300CB	300	Clay Brick	1	50	500	Fully Connected
	FI300HM	300	Hollow Masonry	1	50	500	
	FI300SFW	300	Steel Framed Wall	1	50	500	
Type III Modified Infilled Frame	MIF300CB	300	Clay Brick	1	50	500	Isolation
	MIF300HM	300	Hollow Masonry	1	50	500	Dissipation
	MIF300SFW	300	Steel Framed Wall	1	50	500	Strengthening

Type III corresponds to options available such as partly or fully isolated infills, strengthened infills, infills with dissipation devices or a combination of those (Figure 7). Among these options, for Type III specimens, the most suitable one for each type will be selected after Type II tests.

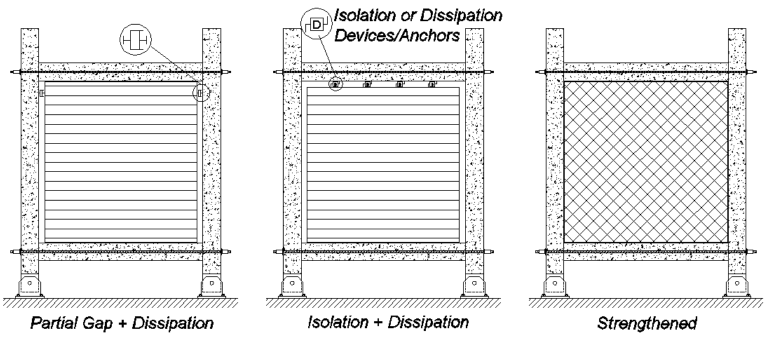

Figure 7 Conceptual Options for Type III Specimens

4.3 *Preliminary Numerical Studies*

For numerical studies, a concentrated plasticity frame model in the computer software Ruaumoko 2D (Carr 2010) has been utilized. Preliminary predictions and their refinements will be made before and after the tests. For Type II specimens, the infills are modelled using the hysteresis model developed by Crisafulli (1997) as shown in Figure 1b-c. The schematic view of the finite element model and the preliminary predictions for the Type I (Bare Frame) and Type II (Infilled Frame) tests have been shown in Figure 8.

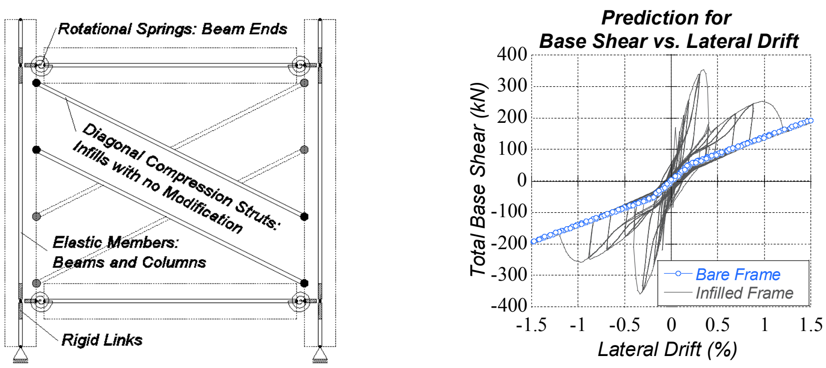

Figure 8 Schematic View of the Model Developed (Left), the Predicted Behaviour of the Bare and Infilled Frames (Right)

5 CONCLUSIONS

In this paper the susceptibility of the infill walls to damage has been emphasized. Although New Zealand standards (e.g. NZS4230) require infill walls to be either properly isolated or fully integrated to the surrounding frame, the required method of proper isolation is not well defined. The purpose of this study is to develop affordable state-of-the-art technological solutions and design guidelines to minimize damage to infill walls. The concept, background on the infill practice in New Zealand and the research programme with preliminary numerical results has been reported.

6 ACKNOWLEDGEMENTS

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REFERENCES:

ACI 374.1-05 Acceptance Criteria for Moment Frames Based on Structural Testing and Commentary. 2005.

Akguzel, U. 2003. Seismic Retrofit of Brick Infilled R/C Frames with Lap Splice Problems in Columns. *MS Thesis.* Department of Civil Engineering, Bogazici University, Istanbul, Turkey.

Akin, E., Ozcebe G., Ersoy U. 2009. Strengthening of Brick Infilled RC Frames with CFRP Sheets. *Seismic Risk Assessment and Retrofitting-Geotechnical, Geological, and Earthquake Engineering*. Vol 10, Ch 18, 367-386.

Calvi, G.M., Bolognini D. 2001. Seismic Response or Reinforced Concrete Frames Infilled with Weakly Reinforced Masonry Panels. *Journal of Earthquake Engineering.* 5:2, 153-185.

Carr, A.J. 2010. Inelastic Dynamic Analysis Program Ruaumoko 2D. *Ruaumoko 2D Manual.* Civil and Natural Resources Engineering Department of University of Canterbury, Christchurch, New Zealand.

Crisafulli, F.J. 1997. Seismic Behaviour of Reinforced Concrete Structures with Masonry Infills. *PhD Thesis.* Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.

Dolsek M., Fajfar P. 2008. The Effect of Masonry Infills on the Seismic Response of a Four-Storey Reinforced Concrete Frame-A Deterministic Assessment. *Engineering Structures.* 30 (2008) 1991-2001.

FRST Retrofit, 2010. Seismic Retrofit Solutions for Research Science and Tech. (FRST) NZ. Christchurch & Auckland. NZ. Available at: http://www.retrofitsolutions.org.nz/index.shtml

GIB Specifications for Drywalls 2006. *GIB Noise Control Systems*. March 2006. www.gib.co.nz

Holmes, I. L. 1965. Concrete Masonry Buildings in New Zealand. 3rd World Conf. on Earthquake Eng., Auckland, NZ, 244-255.

Lee H.S., Woo S.W. 2002. Effect of Masonry Infills on Seismic Performance of a 3-Storey R/C Frame with Non-Seismic Detailing. *Earthquake Engng Struct. Dyn.* 2002;31:353-378.

Magenes G., Pampanin S. 2004. Seismic Response of Gravity-Load Design Frames with Masonry Infills. *13th World Conference on Earthquake Engineering.* August 1-6, 2004, Paper No. 4004, Vancouver, Canada.

Mander, J. B., Nair, B., Wojtkowski K., Ma J. 1993. An Experimental Study on the Seismic Performance of Brick-Infilled Steel Frames with and without Retrofit. *National Center for Earthquake Engineering Research.* Technical Report NCEER-93-0001.

Mosalam, K.M., White, R.N., Gergely, P. 1997. Static Response of Infilled Frames Using Quasi-Static Experimentation. *ASCE Journal of Structural Engineering.* Vol.123, No. 11, 1462-1469.

NZS 95:1935. *New Zealand Standard of Model Building By-Law.* Sections I-X, Part V-VI.

NZSS 595:1952. *New Zealand Specification for Concrete Bricks and Blocks.*

NZSS 1900:1964. *New Zealand Standard of Model Building Bylaw.* Chapter 9.2.

NZS 4230P:1985. *Provisional New Zealand Standard-The Design of Masonry Structures.* Chapter 11.

NZS 4230:2004. *Design of Reinforced Concrete Masonry Structures*, 123-126.

NZS 1170.5:2004. *Structural Design Actions Part 5: Earthquake Actions-New Zealand*, 42-44.

Paulay, T., Priestley, M.J.N. 1992. *Seismic Design of Reinforced Concrete and Masonry Buildings*. Christchurch, San Diego: John Wiley and Sons. 584-595.

Villaverde R. 1997. Seismic Design of Secondary Structures: State of the Art. *ASCE Journal of Structural Engineering.* Volume 123, Issue 8.1011-1019.